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Supply and dispersal of flood sediment from a steep, tropical watershed: Hanalei Bay, Kaua'i, Hawai'i, USA

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Notes

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ABSTRACT

In contrast to many small, mountainous watersheds in temperate coastal regions, where fluvial discharge and wave energy commonly coincide, deposition and reworking of tropical flood sediment can be seasonally decoupled, and this has important implications for coral-reef ecosystems. An understanding of the interaction between tropical flood sedimentation and wave climate is essential to identifying and mitigating effects of watershed changes on coral reefs as urbanization and climate change proceed. Sedimentary facies and isotopic properties of sediment in Hanalei Bay, on the island of Kaua'i, Hawai'i, USA, were used to assess deposition and reworking of flood deposits from the Hanalei River in a case study demonstrating the potential ecosystem effects of runoff from a steep, tropical watershed.

In Hanalei Bay, the youngest and thickest terrigenous sediment was consistently present near the river mouth and in a bathymetric depression that acted as at least a temporary sediment sink. During this 2 yr study, the largest flood events occurred in late winter and spring 2006; substantial terrestrial sediment delivered by those floods still remained in the bay as of June 2006 because oceanic conditions were not sufficiently energetic to transport all of the sediment offshore. Additional sediment was deposited in the bay by a summer 2006 flood that coincided with seasonal low wave energy. In most years, flood sediment accumulating in the bay and on its fringing reefs would be remobilized and advected out of the bay during winter, when the wave climate is energetic. Turbidity and sedimentation on corals resulting from late spring and summer floods during low wave energy could have a greater impact on coral-reef ecosystems than floods in other seasons, an effect that could be exacerbated if the incidence and sediment load of tropical summer floods increase due to urbanization and climate change.

Keywords: coastal sediment, Hawaiian Islands, floods, flood deposits, coral reefs.

INTRODUCTION

Coral-reef ecosystems are widely considered to be threatened by ocean warming and acidification, and by direct human modification of the shoreline (Hughes et al., 2003; Fabricius, 2005; Hoegh-Guldberg et al., 2007). Coastal processes in tropical regions, particularly the interaction between flood sedimentation and wave climate, must be understood in order to identify and mitigate the effects of watershed changes on coral reefs, which can be stressed substantially by terrestrial runoff (e.g., Fabricius, 2005). We investigated the delivery and dispersal of flood sediment in Hanalei Bay, on the island of Kaua'i, Hawai'i, USA, to understand more thoroughly how runoff from a mountainous, tropical watershed could affect sensitive coastal ecosystems.

Anthropogenic changes to coastal watersheds significantly alter the quantity and characteristics of sediment delivered to the ocean (e.g., Syvitski et al., 2005; Warrick and Rubin, 2007). Watershed sediment yield can decrease as a result of dam construction and river regulation, shoreline armoring, slope stabilization by vegetation, or proliferation of paved urban surfaces (Meade et al., 1990; Fletcher et al., 1998; Hill et al., 1998; Runyan and Griggs, 2003; Syvitski et al., 2005), or it can increase due to deforestation (Riestenberg and Sovonick-Dunford, 1983; Jakob, 2000; Montgomery et al., 2000). Introduction of non-native plant and animal species may increase or decrease sediment stability in a drainage basin (Graf, 1978; Lacey et al., 1989; Laughrin et al., 1994; Gabet and

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Dunne, 2002). In rural Hawaiian watersheds, sediment-related concerns that could affect coral-reef health include agricultural runoff, contamination by sewage, increased sediment production due to foraging by feral pigs and goats, and other changes caused by the spread of non-native flora and fauna.

An understanding of coastal systems such as those of the Hawaiian Islands is important not only because of their integration with coral-reef ecosystems, but also because small- and moderate-sized watersheds (10^1–10^4 km^2) along mountainous coasts collectively have greater importance for global sediment production than larger rivers (Milliman and Syvitski, 1992). The best-documented examples thus far of flood-sediment generation and dispersal from small, steep watersheds have come from temperate climates, where sediment production (rainfall and flooding) and reworking (wave and current energy) are strongly coupled during winter storms (e.g., Wheatcroft et al., 1997; Drake, 1999; Sommerfield and Nittrouer, 1999; Ogston et al., 2000; Wheatcroft and Borgeld, 2000; Warrick et al., 2007), or where waves generated by distant storms commonly reach the coast without concurrent local rainfall and flooding (Farnsworth and Warrick, 2007). In contrast, mountainous tropical islands can produce substantial sediment during runoff events in seasons without high waves or strong currents. This study demonstrates the spatial and temporal effects of decoupled flooding and wave energy in a tropical setting, a topic which has been little studied but which has important ecosystem implications, especially as the timing, magnitude, and sediment load of floods are increasingly affected by urbanization and climate change.

Study Area and Background

This 2 yr study focused on sedimentation in Hanalei Bay, covering ~4.4 km^2 on the north shore of the island of Kaua'i (Fig. 1). The 25-km-long Hanalei River drains a 54.4 km^2 watershed before debouching into the bay from the east. Three smaller perennial streams discharge into the bay's southern and western sides. The north-facing Hanalei drainage basin consists of heavily vegetated volcanic ridges and steep gorges that drain 1500-m-high mountains, where rainfall commonly exceeds 10 m yr^{-1}. The lowermost 12 km of the river channel pass through a broad floodplain of middle to late Holocene marine sands overlain by fluvial deposits (Calhoun and Fletcher, 1996) that are used extensively for agriculture. The Hanalei watershed has an estimated sediment yield of 140 ± 55 Mg km^{-2} yr^{-1}, much

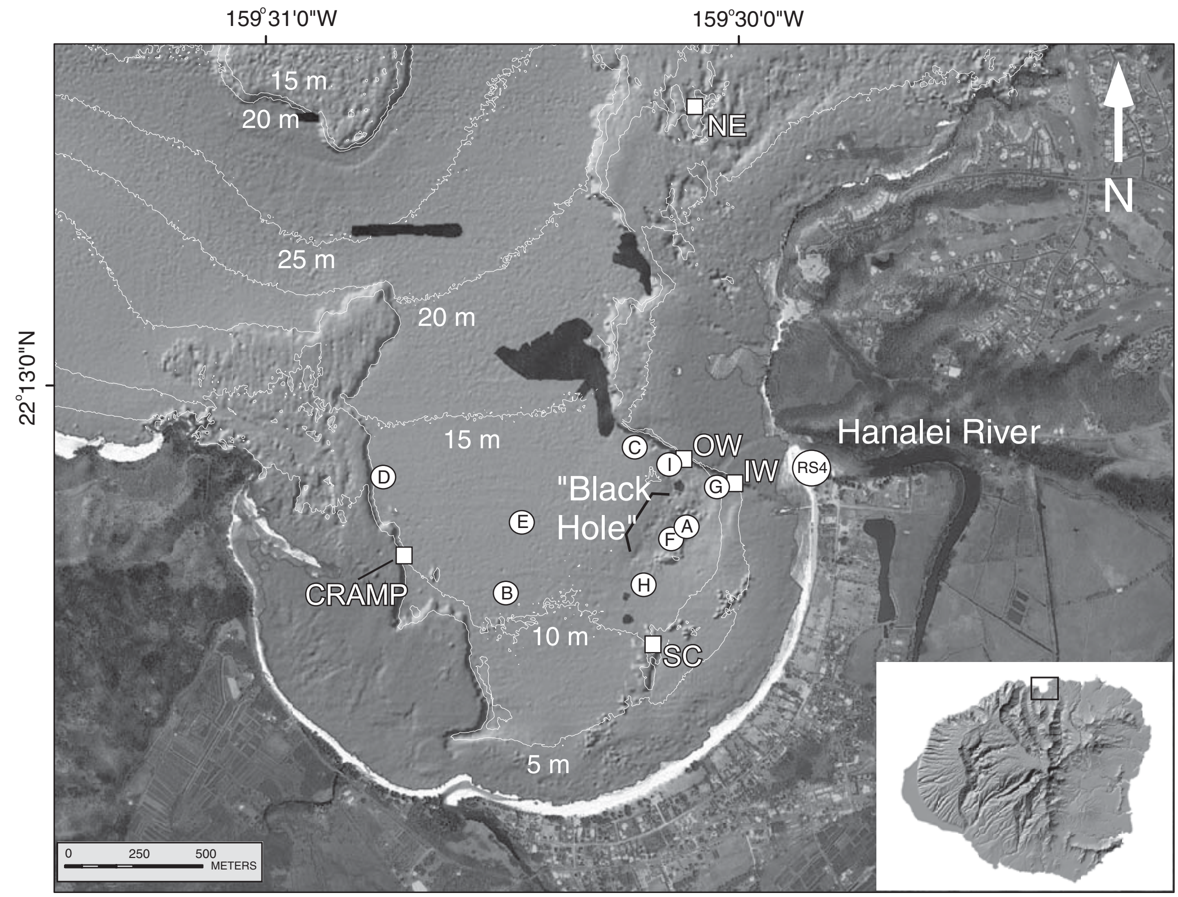


Figure 1. Quickbird satellite image merged with shaded bathymetry, showing Hanalei Bay. Core sites (white circles) are identified by letters A–I. The Hanalei River enters the bay from the east; coral reefs line the perimeter of the bay. The circle marked RS4 shows the location of a river-bed sample collected near the river mouth. White squares indicate the locations of oceanographic instrument packages, including sediment traps that operated during the summers of 2005 and 2006 (Storlazzi et al., 2006, 2007): SC—south-central site, IW—inner wall site, OW—outer wall site, NE—northeast site, CRAMP—Coral Reef Assessment and Monitoring Program site. Bathymetry in this image was interpolated from airborne light detection and ranging (Lidar) data. The isobath interval is 5 m. The inset map shows the location of Hanalei Bay relative to the rest of the island of Kaua'i.

of which is contributed by landslides; ~30% of the annual fluvial sediment load is deposited on the coastal floodplain, and 70% (1.76×10^4 Mg) is delivered to Hanalei Bay (Calhoun and Fletcher, 1999).

The physical environment of the bay is dominated in summer by northeast to easterly trade winds and low wave energy. Winter conditions, typically beginning in October, are characterized by a North Pacific swell that produces wave heights of 2–5 m in the bay with periods of 12–20 s (Moberly and Chamberlain, 1964), approaching the bay typically from the northwest. Occasional low-pressure systems, including tropical cyclones, approach Kaua'i but usually make landfall on the south coast, away from Hanalei Bay.

The seafloor of Hanalei Bay consists of marine carbonate sediment and siliciclastic material derived from the basaltic highlands of the Hanalei River basin (Calhoun et al., 2002). The center of the bay is largely free of indurated substrate, and the nearly flat seafloor is at 10–18 m water depth. At the eastern side of the bay, 500 m offshore of the river mouth, there is a broad depression (~20 m water depth) known locally as the Black Hole because fine-grained, organic-rich suspended sediment obscures visibility (Fig. 1). The coral reef that lines the perimeter of Hanalei Bay hosts ecological communities that, in recent studies of local marine biological diversity, were considered relatively healthy; Hanalei Bay is unusual among Hawaiian coral communities in having increased its live coral cover since the mid-1990s (Friedlander et al., 1997, 2005).

Isotopes Used as Sediment Tracers

Activity levels of radioisotopes ^{7}Be, ^{137}Cs, and ^{210}Pb in sediment samples were measured during this study. All three have been used previously to assess accumulation rates and sources of nearshore sediment. Beryllium-7, a naturally occurring isotope with a 53 d half-life that forms in the atmosphere (Olsen et al., 1986; Baskaran et al., 1993), is concentrated in terrestrial runoff and indicates recent flood deposits in marine systems where the watershed area is much greater than the coastal or estuarine area considered (Canuel et al., 1990; Sommerfield et al., 1999; Allison et al., 2000; Palinkas et al., 2005). Detection of ^{7}Be in sediment indicates exposure to the atmosphere within the past 8 months approximately five half-lives.

Cesium-137 and ^{210}Pb have been used together to estimate accumulation rates and deposition age of sediment (Duursma and Gross, 1971; Nittrouer et al., 1979; Smith and Ellis, 1982; Buesseler and Benitez, 1994; Allison et al., 1998, 2000; Goodbred and Kuehl, 1998; Sommerfield and Nittrouer, 1999). Cesium-137, which has a 30 yr half-life, was added to the environment by nuclear-weapon testing that began in the 1950s, peaked in 1963, and ceased after 1972, with the exception of minor additions from nuclear accidents in 1979 and 1986. Measurable ^{137}Cs indicates that sediment has been in contact with an atmospheric or fluvial source more recently than the 1950s (Livingston and Bowen, 1979; Smith and Ellis, 1982; Miller and Heit, 1986; Golosov, 2007).

Lead-210 is a naturally occurring daughter product in the ^{238}U decay series, and it has a half-life of 22.3 yr. Excess ^{210}Pb (in excess of equilibrium activity supported by parent isotopes in a sediment sample), usually acquired from exposure to fluvial discharge or by scavenging ^{210}Pb from seawater, characterizes sediment deposited or mixed in by biological or physical processes within the past ~100 yr, or five half-lives. In depositional settings near steady state, the excess ^{210}Pb profile can be used to model rates of sediment accumulation and mixing (e.g., Nittrouer et al., 1979; Crusius et al., 2004).

METHODS

To trace the evolution of flood sediment spatially and temporally, sediment cores were collected in Hanalei Bay by divers in June and August 2005 (seven sites) and in June and September 2006 (nine sites). Cores were supplemented by marine sediment traps and by fluvial suspended- and bed-sediment samples. A complete record of the raw sedimentary and geochemical data from all samples can be found in Draut et al. (2006, 2007a).

Hydrologic and Oceanographic Data

Water discharge and suspended-sediment concentration of the Hanalei River were measured at the U.S. Geological Survey (USGS) gaging station 16103000, 8.2 km upstream from the river mouth (http://hi.water.usgs.gov/). Fluvial sediment load was calculated from suspended-sediment concentration measured in water samples collected by an automated pump sampler at the gaging station. Automated samples were calibrated against manual (equal-width-increment) samples collected at discharge ranging from 2 to 410 $m^3 s^{-1}$. A source of error in river sediment-flux estimates presumably arises from the fact that the stream gage is 1.2 km upstream of agricultural fields in the Hanalei watershed. Small plumes of sediment-laden runoff can be seen entering the Hanalei River downstream of the gage, along agricultural areas of the floodplain, but their contribution to the fluvial sediment load has not been quantified.

Wave conditions near Kaua'i are monitored by the National Oceanic and Atmospheric Administration (NOAA); the closest buoy (#51001) is ~270 km WNW of the island (http://www.ndbc.noaa.gov). During the summers of 2005 and 2006, waves and currents were measured in Hanalei Bay by the USGS (Storlazzi et al., 2006, 2007).

Sediment Collection and Subsampling

Sediment cores were collected with a diver-operated handheld coring unit. To reoccupy the same core sites as accurately as possible on each visit, at each site divers deployed a 1 kg weight (with attached float line) from a sea-surface location, the coordinates of which were verified using a global positioning system (GPS) unit with differential correction (core sites are plotted on Fig. 1). Divers descended along the line and collected cores 2–4 m from the weight, far enough to avoid sampling sediment disturbed by the weight. Given an error margin of 3–5 m for the GPS measurements, core sites were reoccupied within ~10 m on each visit. The diver-operated corer used a slide hammer to drive a 10.7-cm-internal-diameter polycarbonate core barrel into the seafloor. Recovered core lengths were typically 30–50 cm. Sedimentary facies were described and sampled during extrusion of sediment from the core barrel.

Two types of sediment traps collected suspended sediment from bay water between June and September 2006. Tube traps (at locations marked SC, IW, OW, NE, and CRAMP in Fig. 1) consisted of a clear plastic tube that was 30 cm long with an internal diameter of 6.7 cm. A baffle was placed in the top of each tube trap to reduce turbulence and minimize disturbance by aquatic organisms (Bothner et al., 2006). Programmable rotating sediment traps (McLane Research Laboratories Inc., 2004) were deployed at two locations (OW and SC; Fig. 1); each rotating trap used a 20-cm-internal-diameter, 75-cm-long cylinder with a funnel in the lower 15 cm of the cylinder to direct settling sediment into one of twenty-one 500 mL plastic bottles. Bottles were mounted on a carousel that rotated a new bottle under the funnel every 4.5 d.

In addition to sediment collected within the bay, grab samples (0–5 cm thick) were obtained from the Hanalei River bed at the river mouth and 2.5 km and 4 km upstream from the river mouth. One sample of fluvial suspended sediment was collected near the river mouth on 6 September 2006, during a discharge of 4 $m s^{-1}$.

Isotope Analysis by Gamma Counting

Activities of ^{7}Be, ^{137}Cs, and ^{210}Pb, decay-corrected to the date of core collection, were measured in 358 samples from the sediment cores (296), sediment traps (49), river water (1), and river bed (12) by counting gamma-ray emissions at the characteristic energy of each isotope. At the USGS laboratory in Woods Hole, Massachusetts, wet sediment samples were homogenized and subsampled. Aliquots weighing ~100 g were freeze-dried to facilitate disaggregation. Samples of known weight (calculated on a salt-free basis) were analyzed on planar germanium detectors (Canberra Industries, Inc., model GS2020S) for 48–96 h (^{210}Pb standard error within 3%). Activity levels of ^{7}Be, ^{137}Cs, and ^{210}Pb were measured using net counts of the 477.6, 661.6, and 46.5 keV gamma-ray peaks, respectively. Excess ^{210}Pb activity was calculated from the ^{214}Pb activity at 352 keV (Livingston and Bowen, 1979; Joshi, 1987). The efficiency of the detectors over the energy range 46.5–661.6 keV was calibrated using Environmental Protection Agency (EPA) standard pitchblende ore in the same range of geometry as the samples. Calibration of the detectors specifically for ^{137}Cs (661.6 keV) was carried out with a standard solution from Isotope Products Laboratory. A correction for self-absorption on all of the isotopes was made based on the geometry of the gamma-counted sample (Cutshall et al., 1983). Accuracy was confirmed by analyses of standard reference materials, which yielded agreement within 3% of certified values.

Isotope inventories (total activity per cm^2 at each core site) were calculated by multiplying the measured activity (in disintegrations per minute per dry gram of salt-free sediment) in each depth interval by the bulk density (g cm^{-3}) and by the core section thickness (cm). The products were summed over the entire core length.

Grain-Size, Carbonate, and Magnetic-Susceptibility Analyses

Grain size and percent carbonate were analyzed in 221 samples selected from the sediment cores (215) and river bed (6) at the USGS sediment laboratory in Menlo Park, California, using methods modified from Carver (1971) and Folk (1974). Approximately 25 g of each sample were soaked in hydrogen peroxide to remove organic material and washed via centrifugation. Samples were wet-sieved using a 2 mm sieve to collect gravel, a 63 μm sieve to collect sand, and a 1000 mL graduated cylinder to collect silt and clay. The gravel and sand fractions were dried and weighed. Silt and clay percentages were determined by pipette analysis based on Stokes' law. A representative subsample was taken from each bulk sediment sample for percent carbonate determination. Total inorganic carbon and percent carbonate were analyzed using a UIC CM5012 CO_2 coulometer and CM5130 acidification module.

Magnetic susceptibility, a measure primarily of the amount of ferrimagnetic minerals (magnetite and titanomagnetite) in a sample, with minor contribution from other Fe-Ti oxide and Fe-bearing minerals, was analyzed in 183 samples from cores at sites A, C, and I (Fig. 1; 143 total samples), sediment traps (15), and fluvial suspended sediment (1) at the USGS laboratory in Denver, Colorado. Measurements were made on dried sediment packed into 3.2 cm^3 plastic cubes and normalized for sample mass. Magnetic susceptibility was measured in a 0.1 mT induction at a frequency of 600 Hz, using a susceptometer with a sensitivity better than ~4 × 10^{-7} m^3 kg^{-1}.

RESULTS

Hydrologic and Oceanic Conditions

Substantial flooding occurred on the Hanalei River in February 2005 (Fig. 2; 95 m^3 s^{-1} peak, the highest at that time since 2002), providing the most recent sediment input to Hanalei Bay before core collection began in June 2005. The February 2005 event introduced the largest pulse of terrestrial sediment to the bay of at least the preceding 18 mo (8670 metric tons over 6 d; suspended-sediment measurements at the USGS Hanalei River gaging station began in 2004). The largest flood events during this study occurred between February and April 2006, when the Hawaiian Islands experienced sustained heavy rainfall. Peak flood magnitude occurred on 21 February 2006, with a daily mean water discharge of 119 m^3 s^{-1}. On that day, the fluvial suspended-sediment load (12,700 metric tons) accounted for nearly a third of the total suspended sediment carried by the Hanalei River that winter. After the 2006 winter–spring floods subsided, the Hanalei River was relatively quiescent until a flood of 46 m^3 s^{-1} delivered 709 metric tons of sediment on 7 August 2006 (Fig. 2). No summer floods occurred in 2005.

Energetic wave conditions prevailed during late winter and spring 2005. The NOAA buoy offshore of Kaua'i recorded a storm in mid-March 2005 characterized by significant wave heights (H_{sig}) >7 m. In contrast to high wave energy in spring 2005, significant wave heights were ~4 m or lower (typically 1–3 m) after mid-April 2006 and remained low throughout the following summer (Fig. 2A). From June through August 2005, significant wave heights were <1 m within the bay, had periods of 2.5–5.9 s, and were driven dominantly by northeast trade winds (Storlazzi et al., 2006); conditions in the summer of 2006 were similar (Storlazzi et al., 2007). Currents in the bay were weak during the summers of 2005 and 2006 (mean flow measured 1 m below the surface at the oceanographic instrument stations on Fig. 1 ranged from 2 to 5 cm s^{-1}); anticyclonic near-surface flow entered the bay in the east and flowed out of the bay in the west. Mean near-bed current velocities (typically 1 cm s^{-1}, measured 1 m above the bed at the same instrument stations) indicated opposite, cyclonic flow. Waves and currents in the western bay were more energetic than in the east, a difference attributed to more direct exposure to trade winds at the western side of the bay (Storlazzi et al., 2006, 2007).

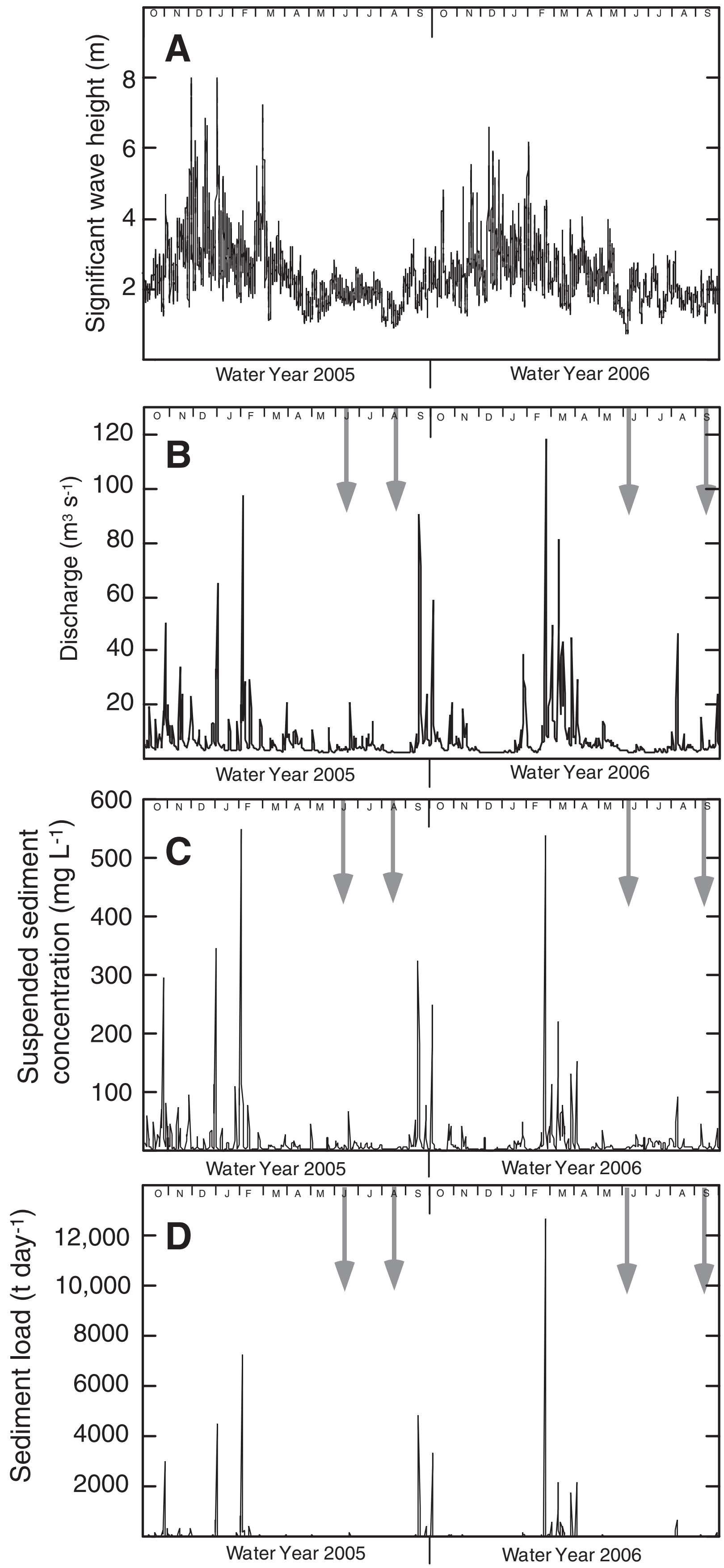
Sediment-Core Profiles

Sediment cores from Hanalei Bay contained two dominant facies: (1) dark, fine-grained, siliciclastic sediment, commonly associated with visually recognized organic material, and (2) carbonate sand (Fig. 3). Magnetic susceptibility (MS) of sediment cores showed an expected inverse correspondence with the amount of nonmagnetic carbonate. The two principal facies formed well-defined horizons, although bioturbation was common. Terrestrial wood debris was also observed on the seafloor by divers in the eastern bay, particularly in 2006. Occurrence of the two main sedimentary facies varied in the bay with space, time, and depth. When sampled from the upper parts of cores, the siliciclastic facies commonly also contained ^{7}Be and ^{137}Cs. The same facies sampled deeper in cores commonly lacked ^{7}Be and in many cases also lacked ^{137}Cs (Fig. 4).

Sedimentary facies, isotope activity, and magnetic susceptibility are shown for two core sites of particular interest in Figures 5 and 6. Site A (Fig. 5) is within the Black Hole bathymetric depression; site C (Fig. 6) is at the base of a coral-reef wall in the eastern bay. Cores from site A were dominated by dark, siliciclastic mud rich in organic matter. This facies, in the upper parts of cores from site A, typically contained appreciable ^{7}Be and ^{137}Cs, especially in June 2006 (Fig. 5). Below ~20 cm, site A sediment was still dominated by siliciclastic mud, but it had little or no ^{7}Be and ^{137}Cs. Sediment at site C, in contrast, consisted mainly of ^{7}Be- and ^{137}Cs-free carbonate sand (Fig. 6). Notably, in June 2006, site C contained two distinct horizons of dark, fine-grained siliciclastic sediment (0–2 cm and 28–34 cm deep) that contained ^{7}Be and ^{137}Cs (Figs. 3B and 6C).

Temporal and spatial variations in Hanalei Bay sediment cores during the study interval are summarized as follows. In June 2005, the

Figure 2. (A) Significant wave height measured at National Oceanic and Atmospheric Administration (NOAA) buoy 270 km WNW of Kaua'i. (B–D) Water and sediment discharge of the Hanalei River, and rainfall in the Hanalei watershed, in water years 2005–2006 (1 October 2004–30 September 2006). Water and sediment discharge were measured at U.S. Geological Survey (USGS) gaging station number 16103000 (8.2 km upstream of the river mouth). (B) Water discharge; arrows indicate times of sediment-core collection in Hanalei Bay. (C) Suspended-sediment concentration (mg L^{-1}) measured at gaging station 16103000. (D) Fluvial sediment load (in metric tons per day) based on a rating curve and suspended-sediment samples analyzed by the Water Resources Division of the USGS.



eastern side of Hanalei Bay (especially the Black Hole) contained an uppermost layer of ^{7}Be-rich, unconsolidated, siliciclastic mud typically 2–4 cm thick (20 cm at site A; Fig. 5A). Sites in the middle and western part of the bay contained almost exclusively carbonate sand free of ^{7}Be and ^{137}Cs. Facies in August 2005 were similar at most sites to those observed in June. When sampled in June 2006, cores from the Black Hole contained fine-grained sediment with high ^{7}Be (>10 dpm g^{-1}), ^{137}Cs (~1 dpm g^{-1}), and excess ^{210}Pb (20–40 dpm g^{-1}) from the seafloor to depths of 10–20 cm (e.g., Fig. 5C). Inventories of ^{7}Be were, in general, substantially higher in June 2006 than at any other time sampled, and Black Hole sites A, F, and I contained ^{7}Be inventories at least an order of magnitude higher than other sites at that time (Fig. 4A). Sites in the middle and western bay remained dominated by carbonate sand, as in 2005, and contained ^{7}Be activity typically <1 dpm g^{-1}, ^{137}Cs <0.5 dpm g^{-1}, and excess ^{210}Pb <10 dpm g^{-1}. The site nearest the river mouth, site G, contained mixed carbonate and siliciclastic sediment showing ^{7}Be, ^{137}Cs, and excess ^{210}Pb activities almost an order of magnitude lower than contemporaneous levels at sites in the Black Hole. As of September 2006, Black Hole core sites A, F, and I were still dominated by siliciclastic sediment, but ^{7}Be activity at the Black Hole sites was 5 dpm g^{-1} or less, while ^{137}Cs and excess ^{210}Pb were comparable to values in June 2006. As in June 2006, site G, near the river mouth, had mixed carbonate and siliciclastic sediment and ^{7}Be, ^{137}Cs, and excess ^{210}Pb almost an order of magnitude lower than contemporaneous levels in the Black

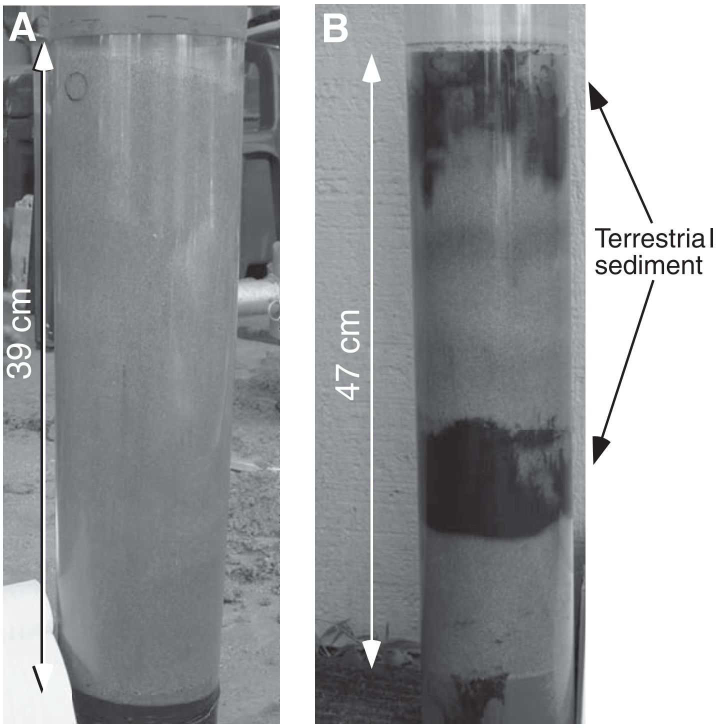


Figure 3. Photographs showing marine and terrestrial sedimentary facies in Hanalei Bay. (A) Homogeneous marine carbonate sediment makes up the core collected at site E in August 2005. (B) Terrestrial flood sediment (black mud, occurring in well-defined horizons but smeared along the edges of the core barrel) is interbedded with marine carbonate sediment in the core collected at site C in June 2006.

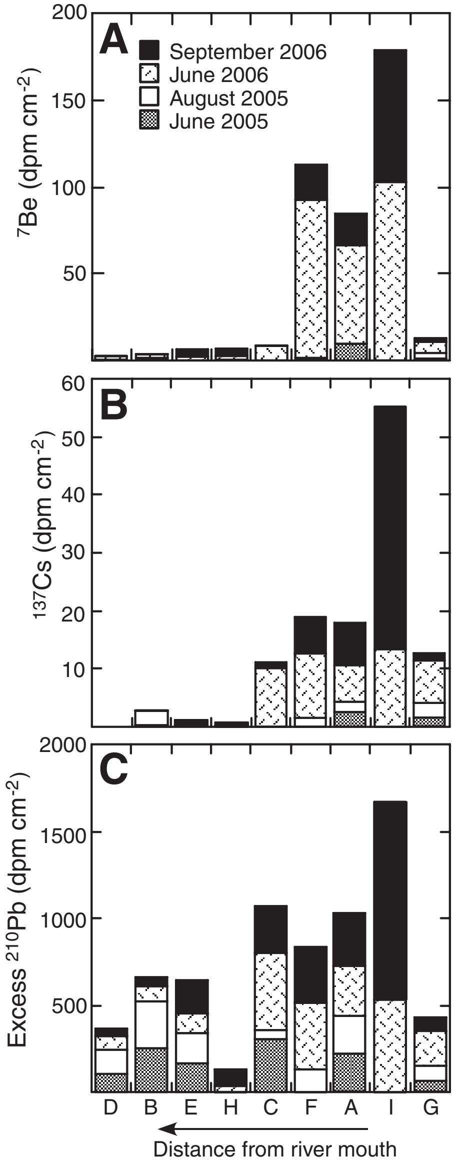


Figure 4. Inventory of (A) ^{7}Be, (B) ^{137}Cs, and (C) excess ^{210}Pb at each core site in Hanalei Bay, in units of disintegrations per minute (dpm) per cm^{2}. The legend in A also applies to B and C. Core sites are identified by letter (locations shown in Fig. 1), and they are arranged in order of their distance from the river mouth. Sites F, A, and I are in the Black Hole bathymetric depression. At site F in June 2005, the full inventory was not recovered due to very short core length (4 cm). Sites H and I were sampled only in June and September 2006.

Hole; cores from the middle and western bay contained almost exclusively carbonate sand free of ^{7}Be, ^{137}Cs, and excess ^{210}Pb.

Marine Sediment-Trap Samples

Marine suspended sediment collected in traps during the summer of 2006 showed similar general patterns to those observed in cores. Activities of ^{7}Be and ^{137}Cs were highest in the eastern bay near the Black Hole and river mouth (^{7}Be as high as 35 dpm g^{-1} at the SC site, and ~6–11 dpm g^{-1} at the IW and OW sites; ^{137}Cs ~ 0.5– dpm g^{-1} at the SC, IW, and OW sites; Fig. 1). Levels of ^{7}Be and ^{137}Cs were substantially lower in the western bay at the CRAMP site (^{7}Be = 5–6 dpm g^{-1} and ^{137}Cs = 0.15–0.19 dpm g^{-1}) and were negligible at the NE site, >1 km northeast of Hanalei Bay (Fig. 1).

DISCUSSION

Sedimentary Facies and Isotopic Signatures

The dark, siliciclastic facies in Hanalei Bay sediment cores is interpreted as terrestrial (fluvial) material deposited primarily by floods. Flood deposits contained a lower proportion of carbonate (and correspondingly higher magnetic susceptibility, where measured) than the coarser-grained marine deposits. Terrestrial sediment was commonly associated with leaf litter, wood fragments, and roots, forming a muddy, peat-like deposit. Occasional rounded siliciclastic pebbles were also recovered. Terrestrial material containing ^{7}Be was interpreted as having been deposited less than eight months before core collection; recent terrestrial sediment was consistently thickest in the Black Hole bathymetric depression. Sediment containing ^{137}Cs but lacking ^{7}Be was inferred to be terrestrial material deposited longer ago than eight months, such that any ^{7}Be had been lost through radioactive decay before core collection. High ^{7}Be and ^{137}Cs activity values in the fluvial suspended sediment support those interpretations (^{7}Be at 23.8 ± 1.59 dpm g^{-1}, ^{137}Cs at 1.68 ± 0.16 dpm g^{-1}). River-bed samples showed ^{7}Be and ^{137}Cs values that were two orders of magnitude lower than values in fluvial suspended sediment (Draut et al., 2007a). This is assumed to be either because older, relict

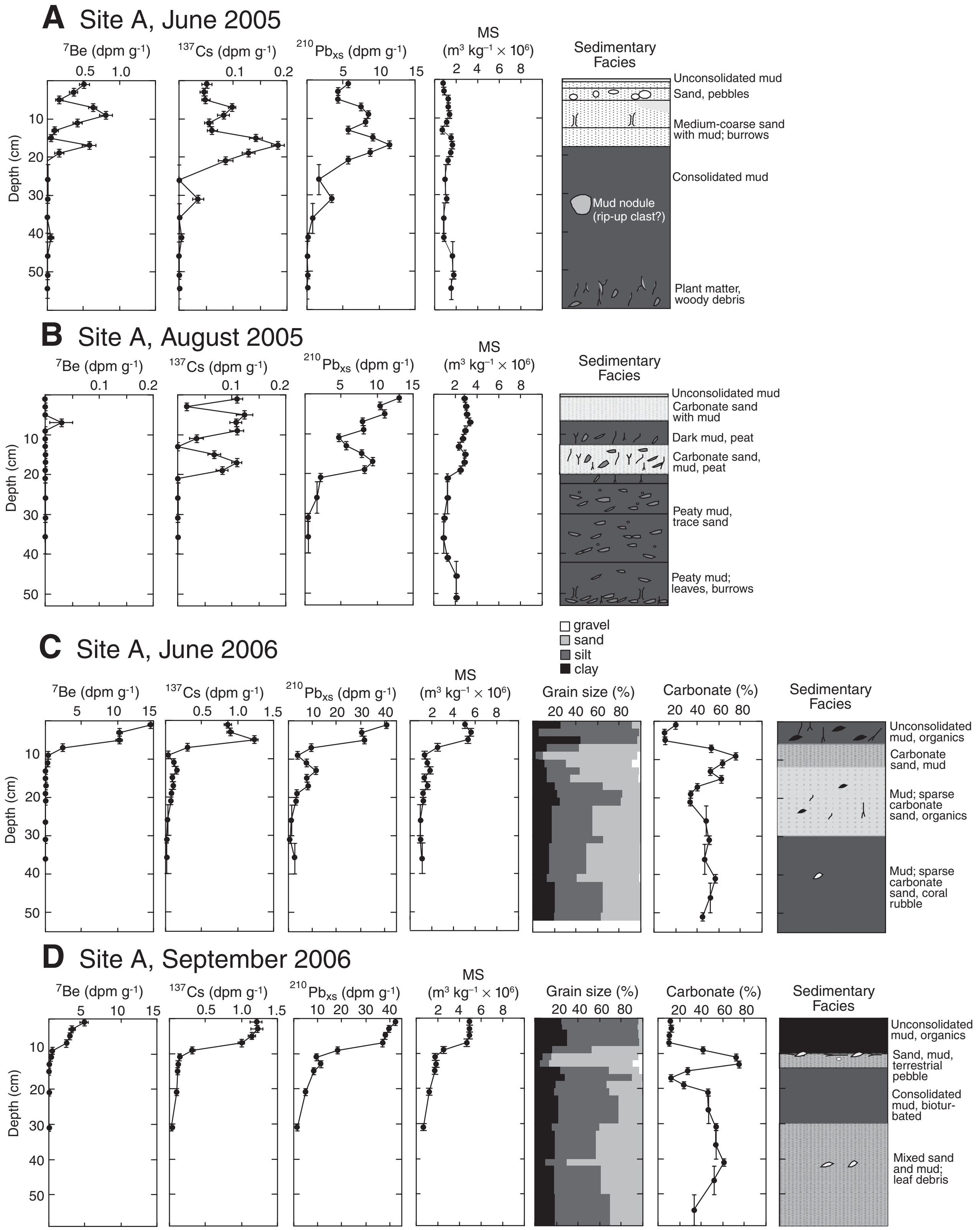


Figure 5. Core stratigraphy at site A, in the Black Hole bathymetric depression. Profiles with depth of (A) ^{7}Be, ^{137}Cs, excess ^{210}Pb, magnetic susceptibility (MS), and sedimentary facies in June 2005; (B) ^{7}Be, ^{137}Cs, excess ^{210}Pb, MS, and sedimentary facies in August 2005; (C) ^{7}Be, ^{137}Cs, excess ^{210}Pb, MS, grain size, percent carbonate, and sedimentary facies in June 2006; and (D) ^{7}Be, ^{137}Cs, excess ^{210}Pb, MS, grain size, percent carbonate, and sedimentary facies in September 2006. The color scheme on the sedimentary-facies diagrams indicates grain size (darker colors represent finer sediment).

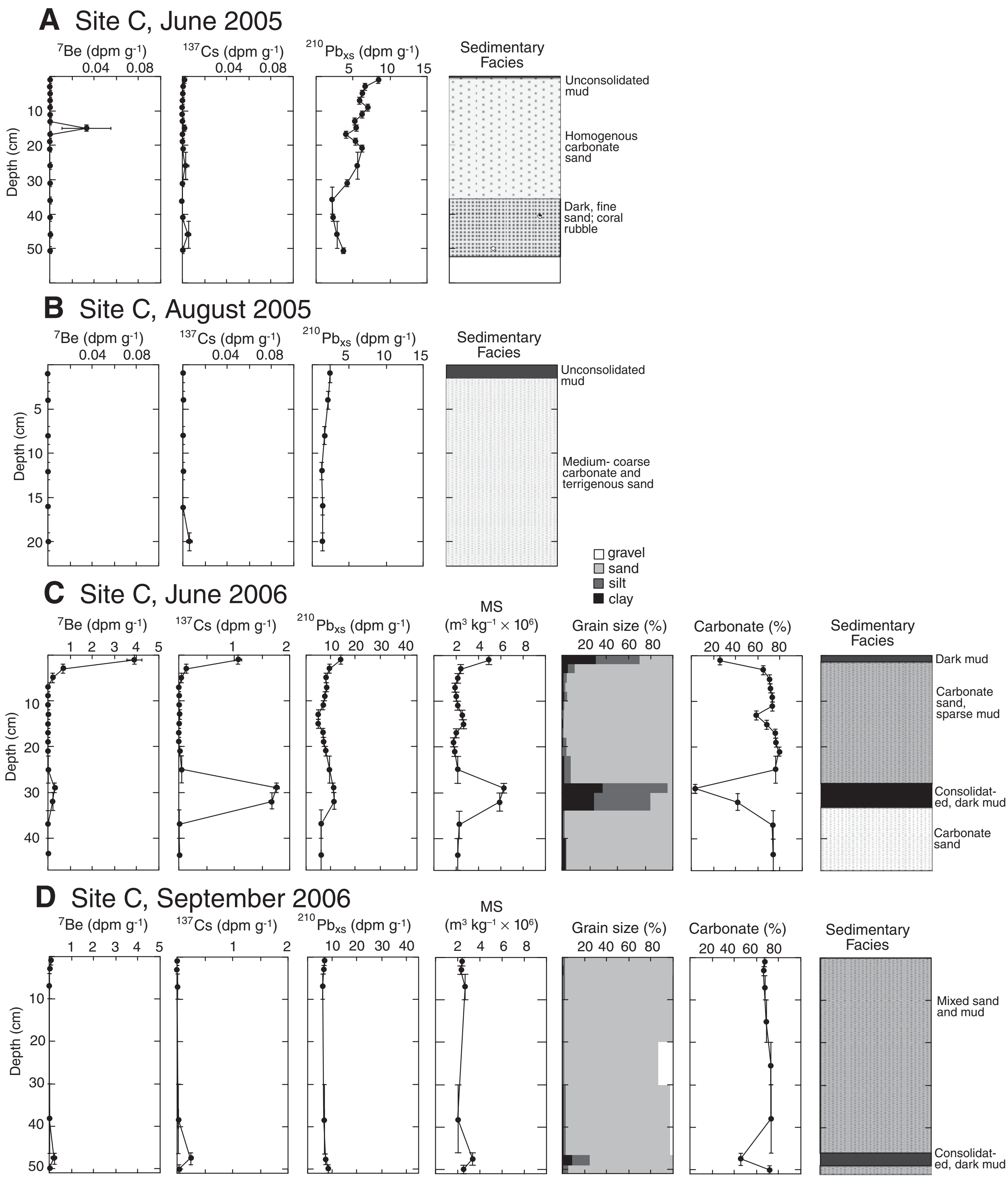


Figure 6. Core stratigraphy at site C, at the east side of the bay along the reef wall offshore of the river mouth. Profiles with depth of (A) ^{7}Be, ^{137}Cs, excess ^{210}Pb, and sedimentary facies in June 2005; (B) ^{7}Be, ^{137}Cs, excess ^{210}Pb, and sedimentary facies in August 2005; (C) ^{7}Be, ^{137}Cs, excess ^{210}Pb, magnetic susceptibility (MS), grain size, percent carbonate, and sedimentary facies in June 2006; and (D) ^{7}Be, ^{137}Cs, excess ^{210}Pb, MS, grain size, percent carbonate, and sedimentary facies in September 2006.

fluvial bed sediment was sampled or because the grain size of the (sandy) bed sediment was much coarser than the suspended sediment (activities of these isotopes decrease as grain size increases because surface area per unit mass decreases with increasing grain size).

Excess ^{210}Pb inventory in the bay did not always track regularly with ^{7}Be and ^{137}Cs, especially in 2005 (Fig. 4). Although excess ^{210}Pb corresponded with ^{7}Be and ^{137}Cs and thus was high in terrigenous sediment at some sites, and was appreciable in fluvial suspended sediment (9.96 ± 0.70 dpm g^{-1}), high excess ^{210}Pb inventory in the western bay sites in 2005, and variable but high excess ^{210}Pb activity in marine sediment traps in 2006 (up to 78 dpm g^{-1} at the CRAMP site, up to 123 dpm g^{-1} at the SC site; Fig. 1) suggest that scavenging from seawater can be a significant source of excess ^{210}Pb in Hanalei Bay sediment. Submarine groundwater discharge could also introduce excess ^{210}Pb to the bay, particularly on the western side; salinity profiles in summer 2005 are consistent with submarine groundwater entering the bay near the CRAMP site (Storlazzi et al., 2006), but ^{210}Pb activity of groundwater was not measured directly during this study. None of the cores presented an excess ^{210}Pb profile that would have characterized steady-state sediment accumulation (one with a well-defined surface mixed layer underlain by gradually decreasing activity and finally by background or “supported” activity; Nittrouer et al., 1979). This is not surprising given the typically energetic wave climate during fall and winter—resuspension events would disturb any established ^{210}Pb profile and allow sediment to scavenge ^{210}Pb from the water column. With frequent seasonal resuspension in the bay, it is not practical here to estimate accumulation rate using geochemical models commonly applied to ^{210}Pb profiles (e.g., Bentley and Nittrouer, 1999; Allison et al., 2000; Noller, 2000).

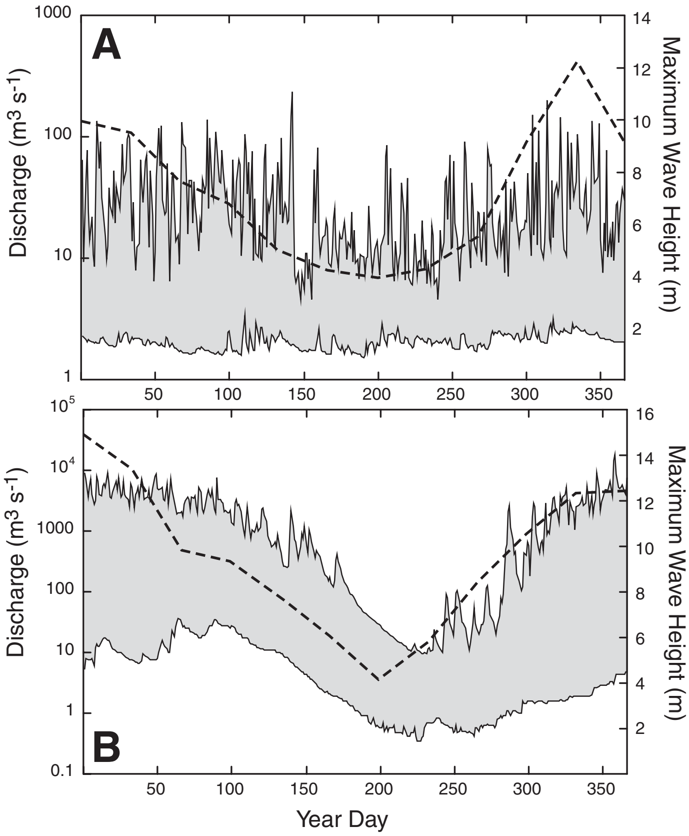


Figure 7. Contrasting seasonal trends in river discharge and wave climate in tropical versus temperate regions. (A) The tropical Hanalei area, Kaua’i, Hawai’i. The gray envelope shows the historical range of daily average Hanalei River discharge (measured at U.S. Geological Survey [USGS] gaging station 16103000 between 1963 and 2007) by year day. The dashed line shows maximum monthly wave height measured at National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) Buoy 51001, 270 km west-northwest of Kaua’i, between 1981 and 2001. (B) The temperate Eel River area, northern California, USA. The gray envelope shows the historical range of daily average Eel River discharge (measured at USGS gaging station 11477000 between 1911 and 2007) by year day. The dashed line shows maximum monthly wave height measured at NDBC buoy 46002, 557 km west of the Eel River mouth, between 1975 and 2001. Strong seasonal coupling of river flow and wave climate occurs in the Eel River example where summer discharge, two orders of magnitude lower than in the wet season, coincides with low wave energy. Other steep, mountainous drainage basins in western North America with watershed areas of 10^1–10^4 km^2 (the Eel watershed is 8000 km^2) show similar trends to those of the Eel basin. Wave climate and river discharge show less seasonal correspondence in the tropical Hanalei example, indicating that flood sediment can enter the tropical coastal ocean months before being substantially reworked.

Interaction of Floods and Wave Climate in Hanalei Bay: River-Ocean Decoupling

Spatial and temporal reworking of flood deposits depends upon the waves and currents that accompany and follow flooding. In this respect, tropical watersheds such as Hanalei can behave differently from well-studied temperate mountainous coastal systems (such as the Eel River, Po River, and southern California watersheds; e.g., Wheatcroft et al., 1997, 2006; Farnsworth and Warrick, 2007) in that sediment can be delivered to the tropical ocean months before being substantially reworked (Fig. 7). Calculations from the historical hydrograph show that although the Hanalei River floods most often in winter, with the highest incidence in March and November, floods with mean daily discharge >40 m^3 s^{-1} (which occurred on 2% of the days from 1963 to 2007) have occurred in every month of the year; the highest historical daily mean flow (236 m^3 s^{-1}), recorded in 1967, occurred in May. The wave climate of the Hawaiian Islands, however, shows stronger seasonality than does the river discharge. Mean monthly H_{sig} ranges from ~1.9 m (June, August, and September) to ~3.1 m (January, February, December); maximum monthly H_{sig} is highest in November (12.2 m) and lowest in July (3.9 m). Events with H_{sig} >6 m do not occur between April and October (Fig. 7A). In summer, Storlazzi et al. (2006, 2007) measured low wave heights (H_{sig} 0.2–0.8 m) and weak currents (~1 cm s^{-1} near the bed, 2–5 cm s^{-1} near the surface) within Hanalei Bay. Therefore, whereas winter storms commonly produce terrestrial runoff and the oceanic energy to rework it, summer (and sometimes spring) Hanalei River floods occur during prolonged low wave energy, when sediment is only minimally reworked.

The decoupling of river discharge and wave energy in the Hanalei watershed occurs because different meteorological conditions produce winter and summer rain. Winter storms in the North Pacific generate both wave swell and precipitation that reach the northern side of the Hawaiian Islands. Summer rainfall is commonly caused by upper-atmospheric disturbances originating in far-field storms, and the waves from these storms do not reach the north side of the islands; warm, tropical air carries enough moisture in summer that, when convection is focused by orography of the islands, weak to moderate atmospheric disturbances from distant storms can cause flood-producing rains. Not every tropical drainage basin displays identical hydroclimatology to that of the Hanalei area, of course—latitude, aspect of the watershed, and proximity to tropical-cyclone paths determine summer wave energy and flooding potential in the tropics—but the ability of steep, tropical watersheds to flood during seasons of low wave energy is important to sedimentary processes in areas other than the Hawaiian Islands as well (Walsh and Nittrouer, 2003).

This study of Hanalei Bay documented one year (2005) in which winter floods were followed by sufficient wave energy to rework sediment and transport it away from shore, and one year (2006) in which wave energy was low enough that substantial late-winter, spring, and summer flood sediment remained nearshore for months. Although the Hanalei River flood of February 2005 was the largest between 2002 and 2005, limited sediment remained near shore by June 2005 (Fig. 4A). The scarcity of fluvial sediment only four months after a substantial flood is attributed to energetic wave conditions, including the mid-March 2005 event, which had H_{sig} >7 m offshore of Kaua'i (Fig. 2A). In contrast, the sedimentary and isotopic signal of the 2006 winter–spring floods was still very apparent as of June 2006 (Fig. 4), which we attribute to low wave energy after the floods ceased. Although terrestrial mud did not thin uniformly away from the river mouth (Cochran et al., 2007), most likely due to some reworking by weak bottom currents and occasional wave activity, the thickest terrestrial sediment was observed in the eastern bay and in the Black Hole. Based on the sediment-core profiles of this study and seafloor samples of Cochran et al. (2007), the total mass of recent (^{7}Be-rich) terrigenous sediment in Hanalei Bay in June 2006 was estimated to be 6250–7490 metric tons, equivalent to ~16%–20% of the fluvial sediment load delivered to the bay between September 2005 and June 2006 (Draut et al., 2007b).

The 46 m^3 s^{-1} Hanalei River flood on 7 August 2006 was smaller than floods during the previous winter, but was still a substantial discharge event for the summer season. Although summer floods do not occur every year, the August 2006 event was not rare (Fig. 7A); recent Hanalei summer floods include 56 m^3 s^{-1} on 26 July 2003, and 91 m^3 s^{-1} on 14 September 2005. Photographs taken by an underwater automated camera station at the outer wall site (Fig. 1) showed that the August 2006 flood deposited sediment on coral colonies there (as well as on the areas sampled by coring; Draut et al., 2007a). Terrestrial sediment delivered by that flood was apparent in the Black Hole as of September 2006, but little sediment from the summer flood was detected elsewhere in the bay. Only the Black Hole showed ^{7}Be inventory higher in September 2006 than could be accounted for by decay of ^{7}Be that was present in June 2006 (by factors of 3 and 1.2 at sites A and I, respectively).

Deposits from the February to April 2006 floods continued to dominate the near-surface sedimentary record in the eastern bay through early fall, even after the addition of newer sediment in the 7 August 2006 flood. This is consistent with the much higher sediment input of the winter–spring floods compared with the 7 August flood (sediment concentration in the winter flood exceeded the sediment concentration on 7 August by a factor of 5.9; Fig. 2). High sediment concentrations in winter floods may have been caused in part by the Hanalei watershed responding differently to prolonged winter rain than to the more episodic summer rain, perhaps producing additional sediment in the winter by landslides and other mass-wasting processes.

Implications for Coral-Reef Ecosystems

Seasonal decoupling of sediment influx and oceanic reworking in the tropics (Fig. 7A) has important implications for coral reefs and other biota. Reef ecosystems in the bay could be affected substantially by either a large summer flood or a large winter flood followed by unusually calm oceanic conditions. Either situation could create substantial turbidity in the photic zone and sedimentation on reefs, reducing photosynthetically available radiation to corals and requiring them to expend energy producing mucus to slough off sediment (Dodge et al., 1974; Dodge and Vaisnys, 1977; Edmunds and Spencer-Davies, 1989; Rogers, 1990; van Katwijk et al., 1993). The productivity and survival of corals can be adversely affected if reefs are buried rapidly by sediment (on the order of 100 mg cm^{-2} day^{-1}), or if water-column turbidity sufficiently inhibits photosynthesis (Rogers, 1990; Fabricius and Wolanski, 2000; Thomas and Ridd, 2005). Quiescent conditions allow sediment to settle and remain on reefs, hard surfaces, and the seafloor within the bay, as observed during this study. Because corals in the Hawaiian Islands spawn in June, July, and August, and require hard surfaces for new recruitment, sediment deposition and persistence on reefs through summer could decrease recruitment and productivity of coral colonies. The potential for summer flood sedimentation to damage corals would increase if land-use changes increase the watershed sediment yield, or if twenty-first–century climate change brings greater summer precipitation to the Hawaiian Islands, as some models suggest (K. Hamilton, 2008, oral commun.).

Retention of substantial terrestrial material in Hanalei Bay on time scales of months is potentially important for other water-quality concerns as well. Organic contaminants and metals (Hg, Pb, Cd, As, Se) in sediment, water, and biological tissue samples collected from the bay in 2001 occurred at levels below those considered by the U.S. Environmental Protection Agency to produce adverse effects on aquatic organisms (Orazio et al., 2007). However, pore-water samples collected in 2005 by Carr et al. (2006) near the river mouth (near our site G) and in the Black Hole were toxic to *Arbacia punctulata* (sea urchin) embryos in the laboratory, though Carr et al. (2006) did not identify the exact nature of the toxins. Therefore, the persistence of ample terrestrial material near the shore on seasonal time scales poses a concern not only for coral productivity but also because land-derived toxins potentially harmful to other species could remain in the bay.

CONCLUSIONS

The winter and spring seasons of 2005 and 2006 saw substantial input of terrestrial sediment to Hanalei Bay, on the north shore of Kaua'i. Oceanic conditions were sufficiently energetic during the spring of 2005 to flush nearly all recent flood sediment out of the bay, and very little remained by the beginning of summer. In contrast, major floods from February to April 2006 were followed by relatively quiescent wave conditions, such that several thousand metric tons of recently delivered terrigenous sediment remained in the bay as of June 2006. Additional sediment was deposited by a summer flood in August 2006. The thickest flood deposits were present on the eastern side of the bay, near the Hanalei River mouth and in the Black Hole bathymetric depression, which acted as at least a temporary sediment sink.

The timing (seasonality) and magnitude of sediment input to the coastal ocean relative to seasonal variations in wave and current energy could have significant ecological consequences for this and other tropical coastal zones. In this respect, the hydroclimatology of steep, tropical drainage basins can differ in an important way from similarly sized mountainous watersheds in temperate regions, where fluvial sediment load is commonly controlled by the same weather systems that generate oceanic energy to rework flood deposits. In the Hawaiian Islands, abundant terrestrial sediment runoff followed by quiescent oceanic conditions in spring, summer, and early fall, whereby sediment (and any associated chemicals and nutrients) remains near shore, could lead to sediment mantling on reefs and hard surfaces. Because water-column turbidity, sediment deposition, and loss of hard-substrate recruitment sites can place ecological stress on corals, these factors might alter or decrease productivity and thereby affect the long-term health of adjacent coral reefs.

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